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A SELECTIVE REVIEW OF THE LITERATURE ON TACTILE SENSITIVITY: 1940-1965

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FOREWORD

This survey was conducted by the Neurophysiology Branch, Biodynamics and ionics Division, Biomedical Laboratory, Aerospace Medical Research Laboratories, Vright-Patterson Air Force Base, Ohio. This literature survey was made in support f Project No. 7232, "Research on the Logical Structure and Function of the Nervous ystem," and Task No. 723202, "Physical and Physiological Mechanisms Involved n the Reception of Acoustic Energy." The study began in October 1965 and was ompleted in December 1965.

This technical report has been reviewed and is approved.

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ABSTRACT

The literature from 1940 to 1965 concerned with the tactile sense has been selectively reviewed. The neurophysiological, psychophysiological, and communicatory aspects of the tactile system were considered. In each of the three areas, representative studies have been reviewed and current trends of research have been indicated.

SECTION I

INTRODUCTION

The purpose of the present study is to survey the literature related to the sense of touch from 1940 to 1965. The author is well aware that some studies from the period in question which have had the sense of touch as the object of investigation have been omitted. A representative sampling of the problems and research trends in the area has been ~~achieved~~.

An attempt has been made to group the studies surveyed into three overall categories: (1) neurophysiological studies, (2) psychophysiological studies, and (3) those studies which had as their primary goal the development of a system of cutaneous communication. Numerous individual studies could fall under more than one of these headings, and in such cases an attempt has been made to place them in the category to which their results are most relevant.

SECTION II

NEUROPHYSIOLOGY

PERIPHERAL

One of the major questions of interest in investigations of tactile* sensitivity has been the question of what are the transducers for touch and the other cutaneous sensations. Until comparatively recently the suggestion by von Frey that the different qualitative sensations arising from stimulation of the skin with specific types of stimuli were due to the selective action of these stimuli upon specific, specialized encapsulated end organs (except for pain which was attributed to free nerve endings) was generally accepted. This positing of a 1:1 correlation between stimulation of a particular type of end organ and the resulting sensation had obvious heuristic value. It apparently afforded the opportunity for crucial experiments and gave rise to any number of investigations which combined to varying extents introspection on the part of the subject, histological examination of the area stimulated, and electrophysiological monitoring of either multiple or single fiber responses to various stimuli.

In recent years this view has come under increasing attack. Consistent failure to demonstrate histologically the presence of encapsulated receptors in the hairy skin, which is as sensitive to touch as the glabrous areas of the body, as well as the fact that the various forms of encapsulation are distributed along a continuum, rather than falling into easily distinguishable classes, has resulted in abandonment of the theory by numerous investigators. Aiding in this abandonment has been electrophysiological evidence indicating that individual fibers may respond to both mechanical and thermal stimulation (refs 32, 33, 35). A recent symposium on cutaneous sensitivity (ref 24) revealed an apparent consensus among the participants

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*Tactile and tactual have been used interchangeably throughout the report.

that Nafe's theory (ref 48) successfully accounted for the known facts of cutaneous sensitivity. This theory holds that the various forms of encapsulation have no functional significance for cutaneous sensitivity and that the bare nerve filaments are essentially the same and serve as universal receptors. The common adequate stimulus for these filaments is considered to be movement, either in relation to themselves or to the tissue which surrounds them. Thus, tactile sensations are considered to arise as a result of movement of the dermal and epidermal tissues, and thermal sensations are considered to arise from the stimulation of filaments terminating in the neighborhood of the thermally labile smooth muscle of the cutaneous arterioles.

Additional evidence cited as supporting the above view was given by Kenshalo and Nafe (ref 38). They described a series of experiments which indicated that rate of movement is the relevant stimulus dimension in arousing tactile sensations and that upon cessation of movement of the stimulus both the subjective sensation and the objective firing of the nerve ceased. In addition Hahn (ref 23) indicated that Löwenstein (ref 43) removed the encapsulation of the Pacinian corpuscle in successive stages down to the bare filament and found no diminution in response to mechanical stimulation. Mendelson and Löwenstein (ref 45) said that although the bare filament of the Pacinian corpuscle did continue to respond, there were indications that the encapsulation served a functional purpose. It apparently served as a filter which prevented the static components of the mechanical stimulus from reaching the nerve ending. Upon removal of the capsule by dissection, the response of the nerve ending to a sustained stimulus was markedly prolonged. There is also other evidence that cessation of movement of the stimulus may not result in cessation of nerve firing for all touch receptors in the skin. Lindbloom (ref 40) in stimulating the glabrous skin of the foot of the monkey found 55 units which discharged only during the rising phase of the stimulus. In these units the discharge frequency was dependent upon the rate of rise of the stimulus. This finding would seem to support Nafe's theory. However, Lindbloom also reported finding 15 units which showed a prolonged discharge when the displacement caused by the stimulus was maintained statically after the end of the rising phase. Similar results were mentioned by Tapper (ref 53). These findings are in apparent contradiction to Kenshalo and Nafe's contention that when movement of the tissues ceases, stimulation ceases.

There are other indications that the possibility of the presence of special encapsulated tactile receptors should not be ignored. A series of separate studies on what appears to be the same type of receptor appears in the literature. Hunt and McIntyre (ref 35) in addition to finding receptors which responded to both tactile and thermal stimuli, as noted above, also reported slowly adapting touch receptors in the cat which responded only when they were directly touched. These receptors were apparently the same as those which Iggo (ref 36) later described. They have a low threshold for mechanical stimuli and give reasonably consistent discharge frequencies during steady stimulation. These receptors are found in cats, dogs, and primates and have a very restricted and localized receptive field, with no overlap of fields between units (ref 53). Adequate stimulation of these units appears to consist of direct compression, as deformation of the skin surrounding them and propagation of traveling waves on the skin is insufficient for excitation (ref 66).

According to Mann and Straile (ref 44) the receptors in question are tylotrich pads, each of which is intimately associated with a tylotrich follicle, a highly specialized skin appendage.

Other experiments may be cited in support of a doctrine of specific receptors or nerves for the sense of touch. Hensel and Boman (ref 32) recorded action potentials from cutaneous afferent nerve fibers in seven conscious male subjects and found that the threshold for eliciting a single impulse in an individual mechanosensitive fiber was the same as that required to have the subject report a tactile sensation. They viewed these results as indicating support for a theory of specific nerve fibers. Sinclair and Glasgow (ref 52) have also reported results which would appear to support the view that individual nerve fibers are quality specific. They reasoned as follows: an individual nerve is known to be composed of different diameter fibers, and upon application of a cold or pressure block the different diameter fibers stop conducting at different times. They applied cold and pressure blocks to a nerve and found that the subjective reports of touch and thermal qualities ceased at different times after application of the block, with touch always failing last. They then concluded that different qualities are associated with different diameter fibers.

On the whole, the question of whether there are specific receptors (either encapsulated endings or different diameter fibers) for specific sensory qualities or whether there are in fact only universal receptors with the perception of a quality being dependent upon spatiotemporal relations in the firing patterns of the stimulated nerves is far from settled. As Zotterman (ref 67) has pointed out, even if it should turn out that the various forms of encapsulation serve only as a protective device, this does not mean that the nerves themselves could not be specific in their action. One of the major shortcomings of much research in this area is the failure to test with a sufficiently broad range of stimulus intensities. Rarely is a study reported which has monitored the response of a nerve to stimuli presented at several levels of intensity. In studying gustation, Pfaffman (ref 49) recorded single fiber responses of the chorda typani nerve of the rat, cat, and rabbit to various chemical stimuli (quinine, HCl, KCl, NaCl) and found that each single fiber preparation was characterized by a different pattern of sensitivity to the four stimuli. Every one of the fibers isolated responded to more than one stimulus, but to varying degrees. An individual fiber might have a relatively low threshold for NaCl, but if KCl were presented in sufficient concentration it would respond. In such a case, the fiber may be viewed as having a relative specificity for NaCl. The situation may well be similar with the sense of touch. The differences between studies which reported units that responded to tactile or thermal stimuli alone and those which reported units that responded to both tactile and thermal stimulation may be due to the area, intensity, and duration of the stimuli employed.

CENTRAL

Wall (ref 62) has examined the nature of the convergence of peripheral fibers onto the primary neurons in the cord. He pointed out that although there is evidence for a specific central pathway for light touch in the dorsal medial-lemniscus system (ref 63), there also exists a system of central common carrier cells in which the

quality of sensation may be encoded as an impulse pattern. All the central cells he investigated served a stable receptive field which did not vary as a function of the state of excitability of the cell. He also noted that these receptive fields were apparently not formed by the presence of an inhibitory area surrounding the excitatory area, as has been reported for cortical (ref 47) and retinal cells (ref 39). He found that all cells which responded briefly to light touch also responded with a prolonged discharge to heavy pressure, and in addition, responded to temperature changes of the skin. Wall suggested that although the peripheral fibers of different diameters may be quality specific, fibers of many different diameters converged on the central cells, so that they responded to all qualities of skin stimulation. He also thought that differences in the pattern of discharge were dependent upon the nature of the stimulus.

Finally, cortical responses to tactile stimulation has also been investigated. Towe and Amassian (ref 54) have reported on the discharge patterns of individual units in the somatosensory cortex of rhesus monkeys following mechanical and electrical stimulation of the digits. They found that the characteristic response following deformation of the skin or movement of the hairs was a high frequency discharge of several spikes, while that following electrical stimulation was often only one spike. The physical intensity of the stimulus was found to be an important parameter, as it influenced the probability of a single unit response, the size of the receptive field of the unit, and the latency of the response. Also, for 40 units the evoked discharge could be prevented by a prior or simultaneous stimulation at a spatially near point on the skin surface. This was true even if stimulation of the nearby point alone would not fire the unit. The duration of the inhibitory effect varied directly as a function of the intensity of the second stimulus and the spatial separation of the two stimuli. In addition, a facilitatory effect was observed in seven units when two separate points were stimulated simultaneously or sequentially. Duration of the facilitatory effect was much shorter than that of the inhibitory effect. Dewson (ref 15) also investigated cortical responses to tactile stimulation, although he was interested specifically in the neural interactions underlying the phenomenon of "funneling" as described by von Békésy (ref 6). Using cats he found that simultaneous presentation of two tactile stimuli evoked primary cortical activity over a more restricted surface than did the same stimuli presented separately. This study was concerned with evoked surface activity and not with single unit activity, as was the case with Towe and Amassian.

SECTION III

PSYCHOPHYSIOLOGY

TOUCH AND VIBRATION

A question which has historically stimulated much research in the area of tactile sensitivity is that of whether vibration and pressure (touch) are different senses with distinct sets of receptors and neural pathways. Geldard (ref 17) supplied an excellent history of the controversy up until 1940 and a rather extensive (214 items) bibliography.

Geldard dealt with the various arguments which had been raised in support of a separate vibratory sense and concluded that there was no need for postulation of such a separate sense. He felt that vibration and pressure were different temporal expressions of the same perceptual pattern of feeling. Hawkes (ref 24) indicated that Geldard's view of the situation has been generally accepted. However, von Békésy (ref 5) reported results which he felt indicated that pressure sensitivity of hairy skin was mediated by means of a nerve net around the sebaceous gland of a hair follicle, while vibration sensitivity was mediated by nerve fibers at the root of a hair. More recently, Verrillo (refs 60, 61) has reported evidence from which he concluded that at least two populations of mechanoreceptors were represented in glabrous skin. His support for this statement is the fact that varying the size of the contactor caused a variation in the vibrotactile threshold function. The smallest contactor gave a flat threshold function across frequency, while the largest contactor gave a threshold function which was strongly inversely dependent upon frequency. Intermediate sized contactors gave functions which fell between the two extremes. Verrillo felt that this indicated the existence of two distinct sets of receptors, one of which integrated stimulus energy over area and time, while the second was independent of these variables. Obviously, the second system could be viewed as mediating pressure, while the first system mediated vibration. Similar results as to the effect of contactor size had been reported by Geldard (ref 17), however, he did not find it necessary to invoke two separate receptor systems in explanation.

PARAMETRIC STUDIES

Among the many parameters of tactile stimulation investigated have been those of rate of stimulus application and depth of stimulus intrusion (ref 37). Employing the method of subjective magnitude estimation, Jones found that depth of stimulus intrusion was the more important parameter. He reported that increasing the rate of application of the stimulus resulted in the faster stimuli being judged only a little more intense, while the judged intensity of the stimulus varied directly with the total linear displacement of the skin. In addition to investigating the effect of contactor size, Verrillo (ref 59) studied the effects of frequency range between 25 and 640 cps; the threshold function assumed a U-shape with the point of maximum sensitivity in the region of 250 cps. Geldard (ref 17) had reported that recomputation of the data of several investigators yielded the same shaped function with the point of maximum sensitivity also being in the region of 250 cps. Similar results were reported by Eijkman and Vendrick (ref 16).

Other parameters of tactile sensitivity to mechanical stimulation are location of the stimuli on the body (different areas of the skin have different thresholds, with the tip of the tongue and the finger tip being among the most sensitive) and temperature of the skin (ref 65). Werner and Mountcastle (ref 66) indicated that skin temperature also influenced the spontaneous activity of the mechanoreceptive fibers they investigated.

Meyer et al. (ref 46) demonstrated that uncertainty on the part of the subject as to the site where stimulation was to occur raised the threshold for tactile stimulation, while Zubek et al. (ref 68) found that prolonged visual deprivation resulted

in increased cutaneous sensitivity. There are reported differences in tactile sensitivity between the right and left sides of an individual's body, depending on whether he is right or left handed (ref 64). Aftanas and Zubek (ref 1) reported a study in which one group of subjects was exposed to a week of no tactual stimulation of a circumscribed area on the left forearm, while a second group experienced a week of constant light pressure to the same area. A third group served as controls. Measures of two-point threshold and tactual fusion were taken before and after each condition. Both measures indicated an increase in sensitivity for the "no-stimulation" group and a decrease in sensitivity for the "constant-stimulation" group. The control group evidenced no change in sensitivity. More interesting was the finding that changes in sensitivity similar to, but less pronounced than, those found on the experimental arm were also reported for a homologous, but not for a nonhomologous, area on the contralateral arm.

Employing electrical rather than mechanical stimulation, Uttal (ref 55) showed that the Roscoe-Bunsen law (Intensity x Duration = Constant) held for the skin. Hahn (ref 22) employed square wave electrical stimulation so as to be able to achieve separate variation of frequency and duration of the stimulus, while holding constant the rate of current increase within each pulse. Using an ascending method of limits and 30 combinations of frequency and duration, he found that changing the frequency of stimulation resulted in little change in threshold. On the other hand, changes in pulse duration had a marked effect on threshold. Hahn concluded that reported rises in tactile threshold as a result of increased frequency of a sinusoidal stimulus were due primarily to the shortening of the half-cycle length rather than to the change in frequency as such.

There are numerous other parametric studies in the recent tactile literature, particularly those employing electrical stimulation. However, since the primary purpose of these studies was to lay a foundation for tactile communication, they will be dealt with in a later section.

TACTUAL AND AUDITORY COMPARISONS

Much of the recent work on the skin has been stimulated by von Békésy's observation that there are striking similarities between the ways the eye, skin, and basilar membrane of the ear make spatial discriminations. Because of this observation, von Békésy initiated a series of studies on tactile phenomena, with the primary goal of obtaining information as to the mode of operation of similar auditory phenomena. The skin afforded a particularly appropriate site to demonstrate the action of traveling waves and provided the means whereby the phenomenon of funneling could be demonstrated, due to the fact that the lateral spread of the traveling waves following stimulation could be objectively measured by the experimenter and the resulting sensations could be easily described by the subject (ref 8). Von Békésy felt that the phenomenon of funneling is due to the fact that any localized stimulus produces not only a local excitation, but also an inhibitory effect in the tissues surrounding the stimulated area. This allows the sharpening of the sensation, even though a relatively large area may be stimulated. He said that this provided some understanding of how the ear was able to discriminate so well between various frequencies, as well as providing an explanation for the phenomenon of Mach rings in vision (ref 10).

Von Békésy also pointed out other ways in which the skin and the ear reacted similarly. He noted that rotating skin sensations and rotating tones (Drehton) had many aspects in common and that subjective magnitude estimates of sensations mediated by the skin and by the ear varied similarly as a function of changes in a number of stimulus parameters (ref 7). He also noted that they differed with respect to pitch perception (refs 9, 11). Vibratory pitch on the skin varies as a function of a number of parameters, e.g., frequency, amplitude, area stimulated, duration of stimulus; while he indicated that auditory pitch is determined primarily by the frequency of the signal and the other variables have only minimal effects. He also found that if the frequency of a vibrator was held constant, increases in amplitude near threshold resulted in a rise in vibratory pitch, as would be expected. However, further increases in amplitude resulted in a drop in pitch.

Following von Békésy's description of the funneling phenomenon on the surface of the skin, a number of studies were initiated to study this phenomenon and the role it might play in tactile masking. Uttal (ref 57) employed electrical pulse stimulation and determined the course of the inhibitory interaction as a function of the spatial difference between stimuli. The fingers were chosen as the site of stimulation. He found that as the distance increased between the finger stimulated with the signal stimulus and the finger stimulated with the masking stimulus, the level of masking dropped. Ethel Schmid (ref 50) varied the temporal distance between stimuli. She also employed electrical stimulation and applied a stimulus of fixed intensity (conditioning stimulus) to one digit and determined threshold at a neighboring digit with other stimuli (test stimuli). The effects of the intensity of the conditioning stimulus and the spatial separation between the conditioning and test stimuli were also investigated. Schmid always applied the conditioning stimulus to the second digit of the left hand, while the test stimuli were applied to either the third or fourth digits of the same hand. The results indicated that the maximum inhibitory effect was achieved when the conditioning stimulus preceded the test stimulus by 1 to 5 msec. As Uttal had indicated, the amount of inhibition was larger when the two digits stimulated were closer together. For a fixed value of time between stimuli, the amount of inhibition was a monotonic function of the intensity of the conditioning stimulus. For one subject, a slight amount of facilitation, rather than inhibition, was observed when a low intensity conditioning stimulus was used. As was mentioned earlier, Towe and Amassian (ref 54) reported a similar facilitatory effect in seven of the cortical units they investigated. Alluisi et al. (ref 3) employed electrical stimulation and stimulated a number of widely separated loci on the chest. They found that when the subject was required to respond as to the number and location of sites stimulated at any one time, there was a large increase in the percentage of erroneous responses as the number of sites stimulated increased. They felt that their results supported a central rather than a peripheral locus of masking, since they employed an electrical stimulus, which is presumed to stimulate nerves rather than peripheral receptors, and because of the wide separation of the points of stimulation.

Sherrick (ref 51) employed mechanical stimuli and stimulated contralaterally as well as ipsilaterally. He also gathered data on the relative effectiveness of steady and pulsed masking stimuli. He found that although the amount of masking was greater if the stimuli were ipsilateral, significant amounts of contralateral

masking did occur. This also was taken as evidence that the phenomenon of masking cannot be explained solely on the basis of a peripheral mechanism. He also found that a pulsed masking stimulus was more effective than a steady one. Of particular interest was the result that when a contralateral steady masking stimulus is employed, the effectiveness of the masker appears to decrease when its intensity goes beyond 40-db sensation level. Sherrick suggested that this may be due to adaptation at the site of the masking stimulus.

Another study which determined whether relationships found to hold in audition could be extended to the tactile sense was that of Verrillo (ref 61). He investigated whether Zwislocki's theory of temporal summation (ref 69) also held for vibrotactile sensitivity. Absolute thresholds were determined as a function of duration of sinusoidal signal, repetition rate of short pulses, and number of pulses. The results indicated that the theory correctly predicted the threshold shift as a function of changes in these parameters. The data were also consistent with auditory findings that threshold shift as a function of duration of sinusoidal signal was independent of signal frequency.

CORRELATION OF PSYCHOPHYSIOLOGICAL AND NEUROPHYSIOLOGICAL MEASUREMENTS

Uttal (refs 56, 58) devised an interesting technique for comparing neurophysiological and psychophysiological responses to tactual stimulation. He employed Dawson and Scott's (ref 14) technique for recording compound action potentials from intact human peripheral nerves and correlated these potentials with subjective magnitude estimations from the subject. The stimuli consisted of electrical pulses. He found that when the stimulus pulse was kept constant in amplitude and duration and only the interval between two successive pulses was manipulated, the neural response to the second pulse decreased in amplitude the shorter the interpulse interval. In all cases the relative subjective magnitude estimations closely paralleled the relative size of the neural responses (ref 58). He next employed three sequential pulses and while keeping total stimulus duration constant manipulated the middle stimulus so as to vary the amplitudes of the individual neural responses (refs 56, 58). The results indicated that the subjective estimates of stimulus intensity were a direct function of the total amplitude of the triple neural response and were independent of the total duration and spacing of the stimuli, except insofar as these influenced the total neural amplitude. From this Uttal concluded that the neural code for the stimulus intensity in the tactile sense is in some way related to amount of neural activity and that temporal spacing may have only an indirect role in intensity coding.

SECTION IV

CUTANEOUS COMMUNICATION

One of the abiding interests in the area of tactile research has been the question of the feasibility of communication by means of the skin. Geldard (ref 17) has provided an excellent review of earlier work employing vibrotactile stimulation for

cutaneous communicatory attempts and it was in his laboratory that the first really successful attempt to communicate via the skin took place (refs 18, 34). This attempt employed three dimensions of vibratory stimuli for coding: (1) three levels of intensity, (2) three levels of duration, and (3) five loci. Various combinations of these dimensions gave a total of 45 distinct vibrotactile patterns which were then employed as the stimuli. Howell found that with less than 70 hours training one subject was able to receive information at a rate equal to 38 words per minute, with greater than 85% accuracy. This rate of information transmission compared favorably with the ability of an individual to receive Morse code and demonstrated that cutaneous communication was feasible. Subsequent work in Geldard's laboratory has been mainly directed toward determining the optimum combinations of parameters and the optimum number of levels within each parameter to maximize information transmission. Alluisi (ref 2) reported that these efforts have indicated that two or three steps of intensity, three or four steps of duration, six or seven different loci in the chest region, and possibly two or three different rates of change of intensity were practical for discrimination. Goff (ref 21) investigated frequency as another possible dimension to be used in coding. She determined the just detectable change in frequency for four frequencies of vibrotactile stimulation (25, 50, 100, and 150 cps) and found that it varied directly as a function of frequency and inversely as a function of intensity. She concluded that subjects could discriminate changes in frequency and that this provided another dimension upon which vibrotactile stimuli could be coded. Goff first equated the frequencies for subjective intensity and thereby circumvented the interdependence of frequency and intensity which Geldard (ref 18) mentioned. Thus even though subjects were able to discriminate changes in frequency, this dimension is apparently of doubtful value in vibrotactile coding.

The dimension which provides maximal information transmission appears to be that of location. In most studies, the placement of vibrators has been limited to the area of the thorax, primarily because of instrumentation limitations. Geldard and Sherrick (ref 19) pointed out that the use of the thoracic region, because of the prevalence of underlying bony tissue, allowed the means whereby the cochlea could interact in what were supposed to be purely cutaneous phenomena. They said that to prevent transmission by bone conduction and resulting auditory contamination of the data, the fleshy parts of the body (arms, legs, abdomen, and thighs) were to be considered the sites of choice. Geldard and Sherrick, employing Bice's (ref 12) compact, versatile vibrator, used 10 different loci on the fleshy parts of the body. They employed various patterns of stimulation, varying both number and location of stimulators, and determined the subject's ability to discriminate among patterns. The results indicated that the number of errors made were determined almost exclusively by the number of overlapping elements in the patterns to be discriminated. Evidently neither number nor location of stimulation as such caused a loss in discriminability.

Other researchers have concentrated on using electrical pulse stimuli rather than mechanical stimuli. The advantages of electrical stimuli, as pointed out by Gilmer (ref 20), are the facts that more control can be exercised over the quality of stimulation and that the effects of the stimulation can apparently be confined to the immediate area of the active electrode, while vibratory mechanical stimulation results in a

diffuse spreading of traveling waves along the surface of the skin. It should not be assumed that because there are no apparent traveling waves along the skin surface electrodes can be located close together without interacting. As has been shown by the numerous tactile masking studies which employed electrical stimulation, electrica stimuli do interact in much the same manner as mechanical stimuli. Just because no traveling waves are apparent is no reason to ignore the fact that there probably is considerable spread of current through the subcutaneous tissues. A very definite limitation of electrical cutaneous stimulation is the fact that there are fairly definite limits beyond which the various parameters of electrical stimuli cannot be varied without causing pain. Much of the present work in this area is directed towards finding the extents of these limits.

One of the more recent attempts to apply audiofrequencies directly to the skin and thereby to hopefully transduce speech more or less directly by way of the skin was that of Anderson and Munson (ref 4). They indicated that the application of audiofrequency sine wave potentials to the skin resulted in two distinct sensations. The first was a burning sensation near the skin surface, while the second was a throbbing sensation in the deeper tissues which seemed to vary as a function of the frequency of the signal. Anderson and Munson felt that this system had definite possibilities for the reception of speech via the skin. Subsequent research has indicated that such efforts to achieve direct transduction of speech patterned sound energy are futile. This is due primarily to the slowness with which cutaneous nerves react relative to auditory nerves and because of the interdependence of stimulus frequency and intensity in the cutaneous sense (ref 2).

Thus, much effort has been devoted to parametric research aimed toward developin a code suitable for information transmission. A systematic program, comparable to that of Geldard for mechanical vibrotactile stimulation, was initiated by Hawkes at the Army Medical Research Laboratory, Fort Knox, Kentucky. When the finger tips were stimulated with sinusoidal electrical stimuli, the amount of current needed to reach threshold increased as the frequency of the stimulating signal increased (ref 29). If perfect identification of the signal is required, only two levels of intensity could be employed, while if maximum transmission of information is desired, three levels may be used. The degree of training the subject received did not apparently make any difference (refs 29, 30). Three levels of stimulus duration were also found to be the optimum, with durations less than 0.5 second resulting in a significant loss of discriminability (refs 25, 31). However, the degree of naivete of the subject did affect his ability to discriminate among stimulus durations. If a highly trained subject was used, four stimulus durations could be employed for cutaneous signaling purposes, provided relatively strong intensity levels were used (ref 26). The optimal number of levels of intensity and duration are the same for both electrical and mechanical cutaneous communication.

A question which must be answered is how does the skin rate as a detector of signals when compared to other sensory organs, particularly the ear. A series of studies (refs 27, 28, 41, 42) has indicated that brief auditory signals were detected with a high degree of efficiency, while the detection of brief cutaneous signals was not as good. Even more important, the probability of detection of an auditory signal

remained constant throughout an experimental session, while probability of detection of a cutaneous signal tended to decrease as a function of time on task. However, Brown et al. (ref 13) have indicated that the presence of competing sensory signals (interrupted or continuous high level noise) did not disrupt the subject's ability to detect and decode cutaneous signals.

Obviously, the skin cannot compete with the eye or the ear in ability to make fine temporal or spatial discriminations, or in speed of information transmission. However, it does have possibilities for certain types of situations where the eyes and ears may be handicapped by the environment, e.g., communication with tank drivers or frogmen. Among the possible applications of cutaneous signals which Gilmer (ref 20) lists are (1) an aid to spatial orientation, (2) to quickly warn the subject of a possibly dangerous situation or to alert him to expect a signal in another sensory channel, e.g., a visual signal, (3) to provide redundancy of information by presenting it simultaneously in a number of sensory channels. Tactile signals might also be employed in various types of feedback loops. For example, if an individual were exerting too much pressure on the gas pedal of a car, a tactile signal to the foot could be used to signal him to ease off. These types of situations usually involve relatively few discriminations on the part of the individual and can be handled quite well by way of the skin. The more elaborate communicatory situations involve a great number of discriminations and require the development of a code by means of which information can be transmitted. Alluisi (ref 2) has made a suggestion which may result in the establishment of a code suitable for the transmission of complex information. He pointed out that the Japanese first learn to read and write by employing 50 basic symbols, which represent a basic syllabic alphabet. This alphabet is bidimensional, with one dimension being vowelness and the other consonantness. Thus, each symbol represents a combination of a consonant and a vowel. A third dimension is employed to transform certain consonants to either a harder or a softer form. Alluisi suggested that a cutaneous code could be devised to correspond to these symbols. The example he cited would consist of five durations (vowelness), 10 loci (consonantness), and two intensities (hardness of consonants). This system would be much simpler than a corresponding English phonetic code and therefore easier to learn. For purposes of demonstrating its feasibility, all that is needed is a subject who reads Japanese. This code has not apparently been tried to date. Although it is known that two levels of intensity and even 10 locations, provided they are distributed across a large part of the body and each signal employs only one location (ref 19), can be discriminated, there is some question as to whether five durations might not be more than can be adequately handled (refs 25, 26).

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13. ABSTRACT

The literature from 1940 to 1965 concerned with the tactile sense has been selectively reviewed. The neurophysiological, psychophysiological, and communicatory aspects of the tactile system were considered. In each of the three areas, representative studies have been reviewed and current trends of research have been indicated.

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